TITLE OF INVENTION

A DETECTOR ARRAY USING A CONTINUOUS LIGHT GUIDE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Not Applicable

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not Applicable

BACKGROUND OF THE INVENTION

1. Field of Invention

[0003] This invention pertains to a light guide for use in association with a detector array for use in imaging applications such as X-ray imaging, fluoroscopy, positron emission tomography (PET), single photon emission computed tomography (SPECT), computed tomography (CT), gamma camera and digital mammography systems. More particularly, the present invention pertains to a continuous light guide for use in association with a plurality of detector arrays.

2. Description of the Related Art

[0004] In the field of imaging, it is well known that imaging devices incorporate a plurality of scintillator arrays for detecting radioactivity from various sources. Each scintillator array is comprised of a plurality of scintillation crystals which interact with incident high energy photons. In Positron Emission Tomography (PET), the scintillators are provided for detecting photon energy peaks at 511 keV. At least a portion of the energy from the photons is absorbed, depending on the atomic number density (N) and effective atomic number (Z) of the scintillator. As the product (N x Z) increases, the absorption probability in the scintillator increases. Absorbed energy in the crystal is converted to lower energy scintillation photons. The scintillation photons are collected by an array of photodetectors comprised of at least one light-sensing element, such as a photomultiplier tube (PMT) or a solid state photo detector. Typical solid state photo detectors include, for example, avalanche photodiodes (APDs), PIN photodiodes and the like.

[0005] It is well known to interpose a light-transmitting media, or light guide, between the scintillator arrays and the photo-detector array. The light guide is tuned using several known methods. In one such method, slots of various depths are defined in the light guide to channel the scintillation light and enhance the positioning information of the crystals. In a further such method, a reflective material such as paint is applied at various paint levels on the side surfaces of the scintillation crystals in order to channel the light to obtain uniform flood source images.

[0006] Conventional nuclear imaging systems consist of detector blocks, each of which is a modular unit in square or rectangular scintillator arrays with the dimension of MxN crystals. Alternatively, gamma cameras in nuclear imaging have a continuous scintillator, rather than pixilated, and a continuous light guide. The physical properties of the scintillator crystal play an important role on the performance of the detector system. High stopping power, short decay time and high light yield are the most desirable features for a scintillator. Crystals that have a relatively longer decay time limit the count rate capability when the imaging system is exposed to high levels of activity in the field-of-view (FOV).

[0007] It is common practice, when constructing scintillator arrays composed of discrete scintillator elements, to pack the scintillator elements together with a reflective medium interposed between the individual elements fully covering at least four sides of the scintillator element. The reflective medium serves to collimate the scintillation light to accurately assess the location at which the radiation impinges upon the detectors. The reflective medium further serves to increase the light collection efficiency from each scintillator element as well as to control the cross-talk, or light transfer, from one scintillator element to an adjacent element. Reflective mediums include reflective powders, reflective film, reflective paint, or a combination of materials.

[0008] Conventionally, scintillator arrays have been formed from polished crystals that are hand-wrapped in reflective PTFE tape and bundled together, or alternatively, glued together using a white pigment such as MgO, $BaSO_4$ or TiO_2 mixed with an epoxy or RTV. In a further alternative, the crystals are painted with tuned reflective paint partitions and glued with an epoxy to form the block.

[0009] Another approach utilizes individual reflector pieces that are bonded to the sides of the scintillator element with the aid of a bonding agent. This process requires iterations of bonding and cutting until a desired array size is formed.

[0010] Other devices have been produced to form an array of scintillator elements. Typical of the art are those devices disclosed in the following U.S. Patents:

Patent No.	**Inventor(s)**	**Issue Date**
3,919,556	W.H. Berninger	Nov. 11, 1975
3,936,645	A.H. Iverson	Feb. 3, 1976
4,749,863	M.E. Casey *et al.*	June 7, 1988
4,914,301	Y. Akai	Apr. 3, 1990
4,982,096	H. Fujii *et al.*	Jan. 1, 1991
5,059,800	M.K. Cueman *et al.*	Oct. 22, 1991
5,319,204	W.H. Wong	June 7, 1994
5,453,623	W.H. Wong *et al.*	Sept. 26, 1995
5,753,917	J.C. Engdahl	May 19, 1998
6,087,663	C. Moisan *et al.*	July 11, 2000
6,292,529	S. Marcovici *et al.*	Sept. 18, 2001
6,462,341	G. Muehllehner	Oct. 8, 2002

[0011] Of these patents, the '645 patent issued to Iverson discloses a radiation sensitive structure having an array of cells. The cells are formed by cutting narrow slots in a sheet of luminescent material. The slots are filled with a material opaque to either light or radiation or both. The '800 patent issued to Cueman *et al.*, discloses a similar scintillator array wherein wider slots are formed on the bottom of the array.

[0012] Wong, W.H. *et al.*, in "An Elongated Position Sensitive Block Detector Design Using the PMT Quadrant-Sharing Configuration and Asymmetric Light Partition," *IEEE Transactions on Nuclear Science*, Vol. 46, No. 3, 542-545 (1999), discloses a block design wherein seven (7) monolithic BGO slabs are painted with light-blocking reflective patterns on their boundaries. The slabs are then glued together to form a block. The block is then cut orthogonally with respect to the glued seams and painted and glued again in like fashion. A 7 x 7 array is thus defined. The reflective patterns are unclear from the disclosure, but appear to be defined on ly for the cut portions analogous to the '863 patent discussed below, such that the reflective areas increase toward the central portion of the array.

[0013] As discussed, most of the aforementioned methods also require a separate light guide attached to the bottom of the detector array to channel and direct the light in a definitive pattern on to a receiver or set of receivers such as photomultiplier tubes or diodes. The '863 patent issued to Casey *et al.*, discloses a two-dimensional photon position encoder system and process which includes a detector for enhancing the spatial resolution of the origin of incident photons of gamma rays. A plurality of scintillator elements interact with the incident photons and produce a quantifiable number of photons which exit the scintillation material members. A tuned light guide having a plurality of radiation barriers of predetermined lengths define slots which are operatively associated with one of the scintillator material members. The slots serve to enhance the predictability of the statistical distribution of photons along the length of the slotted light guide. A detector detects the distribution of the photons at pre-selected locations along the length of the slotted light guide.

[0014] Berninger, in the '556 patent, discloses a scintillator on which impinge incident collimated gamma rays. Light pulse output from the scintillator is detected by an array of photoelectric tubes, each having a convexly curved photocathode disposed in close proximity to the scintillator.

[0015] In the '204 (Wong) and '623 (Wong *et al.*) patents, a PET camera is disclosed as having an array of scintillation crystals placed next to other arrays either around or on opposing sides of a patient area. An array of light detectors is positioned next to four adjoining quadrants of four respective scintillation crystal arrays to detect radiation emitted from the four quadrants of each array. The crystals within the arrays are selectively polished and selectively bonded to adjoining crystals to present a cross-coupled interface which can tunably distribute light to adjoining light detectors. The crystal arrays are formed by optically bonding slabs of crystals into a "pre-array" and then cross-cutting the "pre-array" from one or more sides to form the final array. Wong *et al.* disclosed that the grooves may be optically treated, such as with white reflective fillers, for further optical control within the array.

[0016] Engdahl, in his '917 patent, discloses a scintillation camera including a scintillation crystal assembly having multiple crystal layers for interacting with various photon energy levels. The camera is disclosed as performing imaging of conventional nuclear medicine radioisotopes as well imaging of high energy isotopes used in PET applications. The multiple crystal layers have the effect of doubling the sensitivity of the camera to high energy photons, while retaining the performance characteristics needed for conventional low energy photon imaging. According to one embodiment disclosed by Engdahl, the '917 device includes a scintillation crystal having a first layer composed of NaI(T1) and a second layer composed of CsI(Na). A collimator is provided for collimating photons incident on the crystal. An array of photomultiplier tubes is provided for detecting and localizing scintillation events within the crystal. The photomultiplier tubes are mounted on a glass lightpipe.

[0017] In the '341 patent, Muehllehner discloses a positron emission detection scanner including a first plurality of detecting elements arranged in a first two-dimensional geometrical array. The detecting elements are provided for communicating light from a scintillation event. A light guide is provided for receiving light from the scintillation events from each of the detecting elements, and then transmitting the light to an array of photodetectors arranged in a second two-dimensional geometrical array, the alignment of the light sensing members being independent of the detecting elements.

[0018] Moisan *et al.*, in the '663 patent, disclose light guides capable of encoding the transverse and longitudinal coordinates of light emission induced by the interaction of photons in an array of a plurality of the light guides. Each light guide has at least two discrete crystal segments adjacently disposed along a common longitudinal axis of the light guide. Between adjacent segments is a boundary layer having less light transmission than the light transmission of the crystal segments. A light absorbing mask is provided to increase light adsorption in a segment. Photons entering the light guide cause the emission of scintillation light which is delivered in different and resolvable quantities to light sensing devices.

[0019] Also of interest is Anger H. "Scintillation camera", Reviews of scientific instrumentation, 29(1):27-33, 1958.

BRIEF SUMMARY OF THE INVENTION

[0020] A detector for use in imaging applications such as X-ray imaging, fluoroscopy, positron emission tomography (PET), single photon emission computed tomography (SPECT), computed tomography (CT), gamma camera and digital mammography systems is provided. The detector of the present invention includes an array of detector arrays, an array of photodetectors, and a continuous light guide disposed between the detector arrays and the photodetectors. The detector arrays, as well as the photodetectors are arranged in various patterns as prescribed by the particular application. The light guide is continuous over the entire area of the photodetectors and detector arrays. The thickness of the light guide is optimized based on the shape of the photodetector array. Because the light guide is fabricated as a continuous member, having no cuts or slots, the time and expense required to fabricate the light guide is minimized.

[0021] At least one detector array is positioned on a continuous light guide, which is in turn positioned above an array of photodetectors. The photodetectors may be placed in a rectangular, hexagonal or other array as prescribed by a particular application. Each detector array includes at least one scintillator element for use in association with an imaging device. The array is fabricated such that location of the impingement of radiation upon an individual scintillator element is accurately determinable. Each array defines an M x N array of scintillator elements, where "M" and "N" are independently selectable, and where "M" is less than, equal to, or greater than "N", and where "M" and "N" are at least one. The scintillator elements define a cross-section of one or a combination of more than one geometric configuration such as circular, triangular, rectangular, hexagonal, and octagonal.

[0022] A mechanism for maintaining the relative positions of the individual scintillator elements with respect to each other is provided. The mechanism is a retainer disposed about the outermost scintillator elements to maintain the relative positions of the individual scintillator elements. The retainer is further provided to enhance the separation between the individual detector arrays to define distinct boundaries between the position profiles of the scintillator arrays. The retainer is fabricated from conventional materials such as molded plastic, shrink wrap, rubberized bands, tape or a combination of like materials may be used to enclose or hold the array together in a tight, uniform fashion. Between each of the individual scintillator elements is disposed either an air gap, a light partition, or a combination of both. The light partitions are applied or placed in the array at any selected locations between the scintillator elements in order to optimize the resultant position profile map. The height of the light partitions and the position of the light partitions within the array are selected to optimize the light transmission between the scintillator elements.

[0023] The existence or non-existence of a light partition dictates the amount of light sharing that occurs between scintillator elements. Air gaps are formed by the absence of a bonding agent between scintillator elements. The air gap between the scintillator elements, regardless of the presence of partial reflector partitions, serves to control the transmission used for early light sharing and reflection of the scintillation light within the scintillator elements. The air gap changes the total angle of reflection due to the significant index of refraction change, which results in an increase in the number of photons reflected at the crystal surface and minimizes the number of photons absorbed in the reflective material. With no light partitions, the packing fraction of the array increases to greater than 95%, and, as a result, so does the detector efficiency of the camera.

[0024] The scintillator elements are bonded to the light guide using a bonding agent. The light guide is positioned above a plurality of photodetectors. The thickness and material of the light guide is selected to optimize the light guide for the geometrical set up of the photodetectors and the light emission properties of the scintillator elements, respectively. The scintillator elements disposed within the array serve to detect an incident photon and thereafter produce a light signal corresponding to the amount of energy deposited from the initial interaction between the photon and the scintillator element. The structure of the array serves to reflect and channel the light down the scintillator element, through the light guide and to the coupled photodetector. The signal generated by the photodetector is then post-processed and utilized in accordance with the purpose of the imaging device.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0025] The above-mentioned features of the invention will become more clearly understood from the following detailed description of the invention read together with the drawings in which:

FIG. 1 is a perspective illustration of one arrangement of the detector arrays, the array of photodetectors, and the continuous light guide of the present invention;

FIG. 2 is an elevation view of the arrangement of the detector arrays, the array of photodetectors, and the continuous light guide illustrated in FIG. 1;

FIG. 3 is a top plan view of the arrangement of the detector arrays, the array of photodetectors, and the continuous light guide illustrated in FIG. 1, showing the relative disposition of the detector arrays with respect to the photodetectors;

FIG. 4 is a perspective illustration of a further arrangement of the detector arrays, the array of photodetectors, and the continuous light guide of the present invention;

FIG. 5 is an elevation view of the arrangement of the detector arrays, the array of photodetectors, and the continuous light guide illustrated in FIG. 4;

FIG. 6 is a top plan view of the arrangement of the detector arrays, the array of photodetectors, and the continuous light guide illustrated in FIG. 4, showing the relative disposition of the detector arrays with respect to the photodetectors;

FIG. 7 is a schematic illustration of the relative disposition of a detector array with respect to an a 3 x 3 rectangular array of photodetectors;

FIG. 8 is a position profile map acquired by flood irradiating the detector array of FIG. 7 with a radioactive point source;

FIG. 9 is a graphical illustration of the energy peaks of each crystal in a single row of crystals of the detector array used to acquire the position profile map of FIG. 8;

FIG. 10 is a row profile of the single row of crystals of the detector array used to acquire the position profile map of FIG. 8;

FIG. 11 is a schematic illustration of the relative disposition of a detector array with respect to a hexagonal array of seven photodetectors;

FIG. 12 is a flood source image acquired by flood irradiating the detector array of FIG. 11 with a radioactive point source;

FIG. 13 is a row profile of the single row of crystals of the detector array used to acquire the position profile map of FIG. 12;

FIG. 14 is a graphical illustration of the energy peaks of each crystal of the detector array used to acquire the position profile map of FIG. 12;

FIG. 15 is a schematic illustration of the relative disposition of two detector arrays with respect to a hexagonal array of ten photodetectors;

FIG. 16 is a position profile map acquired by flood irradiating the detector array of FIG. 15 with a radioactive point source, the two detector arrays having no reflectors; and

FIG. 17 is a position profile map acquired by flood irradiating the detector array of FIG. 15 with a radioactive point source, the two detector arrays having reflectors such as those illustrated in FIG. 2.

DETAILED DESCRIPTION OF THE INVENTION

[0026] A detector for use in imaging applications such as X-ray imaging, fluoroscopy, positron emission tomography (PET), single photon emission computed tomography (SPECT), computed tomography (CT), gamma camera and digital mammography systems is provided. The detector of the present invention includes at least one detector array, an array of photodetectors, and a continuous light guide disposed between the detector arrays and the photodetectors. The detector arrays, as well as the photodetectors are arranged in various patterns as prescribed by the particular application. The light guide is continuous over the entire area of the photodetectors and detector arrays. The thickness of the light guide is optimized based on the shape of the photodetector array. Because the light guide is fabricated as a continuous member, having no cuts or slots, the time and expense required to fabricate the light guide is minimized. Illustrated the Figures are various arrangements of the detector arrays, the array of photodetectors, and the continuous light guide of the present invention.

[0027] FIGS. 1-3 illustrate an array of detector arrays **12** being positioned on a continuous light guide **24** which is in turn positioned above a 6x6 rectangular array of photodetectors **26**. FIG. 3 most clearly illustrates the relative positions of the detector arrays **12** with respect to the photodetectors **26**. Similarly, FIGS. 4-6 illustrate an array of detector arrays **12** being positioned on a continuous light guide **24** which is in turn positioned above a hexagonal array of photodetectors **26**. FIG. 6 most clearly illustrates the relative positions of the detector arrays **12** with respect to the photodetectors **26**.

[0028] Each detector array includes a plurality of scintillator elements **14** for use in association with an imaging device (not illustrated). The array **12** is fabricated such that location of the impingement of radiation upon an individual scintillator element **14** is accurately determinable. Each array **12** defines an M x N array of scintillator elements **14**. "M" and "N" are independently selectable, with "M" being less than, equal to, or greater than "N", and "M" and "N" are at least one. The scintillator elements **14** define a cross-section of one or a combination of more than one geometric configuration such as circular, triangular, rectangular, hexagonal, and octagonal.

[0029] A mechanism **18** for maintaining the relative positions of the individual scintillator elements **14** with respect to each other is provided. In the illustrated embodiment of FIG. 1, the mechanism **18** is a retainer disposed about the outermost scintillator elements **14** to maintain the relative positions of the individual scintillator elements **14**. The retainer **18** is further provided to enhance the separation between the individual detector arrays **12** to define distinct boundaries between the position profiles of the scintillator arrays **12**. The retainer **18** is fabricated from conventional materials such as molded plastic, shrink wrap, rubberized bands, tape or a combination of like materials may be used to enclose or hold the array together in a tight, uniform fashion, as well as to provide reflectivity. Although illustrated as spanning only a portion of the height of the array **12**, some applications may include more than one retainer **18**, or may include a retainer **18** which spans the entire height of the array **12**. Further, while illustrated as being disposed at the upper end of the scintillator array **12**, it will be understood by those skilled in the art that the mechanism **18** may be disposed at any height along the scintillator array **12** as required.

[0030] Between each of the individual scintillator elements **14** is disposed either an air gap **16**, a light partition (not illustrated), or a combination of both. The light partitions are applied or placed in the array **12** at any selected locations between the scintillator elements **14** in order to optimize the resultant position profile map. The height of the light partitions and the position of the light partitions within the array **12** are selected to optimize the light transmission between the scintillator elements **14**.

[0031] In the illustrated embodiment, air gaps **16** are defined between the individual scintillator elements **14**, as opposed to light partitions. The existence or non-existence of a light partition dictates the amount of light sharing that occurs between scintillator elements **14**. To form an air gap **16**, no bonding agent is used between scintillator elements **14**. The air gap **16** between the scintillator elements **14,** regardless of the presence of partial reflector partitions, serves to control the transmission used for early light sharing and reflection of the scintillation light within the scintillator elements **14**. The air gap **16** changes the total angle of reflection due to the significant index of refraction change, which results in an increase in the number of photons reflected at the crystal surface and minimizes the number of photons absorbed in reflective materials used in prior art embodiments as discussed above. With no light partitions, the packing fraction of the array **12** increases to greater than 95%, and, as a result, so does the sensitivity of the camera.

[0032] In the illustrated embodiments, the detector arrays **12** are LSO scintillator arrays of 13 x 13 scintillator elements **14** having a pixel size of 4 x 4 x 20 mm^3. The light guide **24** is an 18 mm-thick polished light guide fabricated from Lucite®. The photodetectors **26** are 2 in diameter photomultiplier tubes (PMTs) spaced approximately 2 mm apart. It will be understood that the photodetectors **26** may be spaced other than at 2 mm depending upon the particular application. The detector arrays **12** are provided with a 0.08 mm thick and 8 mm tall mechanism **18** around them. A reflector sheet such as Lumirror® may be placed on the top side of the detector arrays **12** to increase light output. Because there is no reflector between the scintillator elements **14** in the each array **12**, packing fraction of the array **12** is over 99%.

[0033] In other embodiments (not illustrated), the light transmission may be optimized by providing at least a partial light partition disposed between at least a portion of the individual scintillator elements **14**. For example, in one embodiment, a variable height reflective light partition is provided between selected scintillator elements **14**, with the light partitions extending from the bottom surface of the array **12** and terminating toward the top surface. The height of the light partitions gradually decreases from the outermost light partitions to the center of array **12**, where only air gaps **16** are provided.

[0034] Although not illustrated, the light transmission may be further optimized by varying the optical transmission properties of the scintillator surface or the reflective light partitions, such as, but not limited to, varying the thickness of the light partitions, and varying the optical density of the light partitions.

[0035] When used, the light partitions of the array **12** may be fabricated using one or more of a variety of processes utilizing materials including reflective powders, plastics, paints, polyvinyl alcohol, ceramics, films, and other highly reflective components. The light partitions are dimensioned at various lengths and thicknesses to accommodate various sized scintillator elements **14**, as well as to optimize transmission properties. The array **12** is constructed to have parallel scintillator elements **14** defining either a substantially planar array **12** or an array having an arcuate configuration.

[0036] Alternatively, the light partitions may be fabricated from a reflective film such as 3M VM2000® reflective film. The film is cut to varying heights and attached to the different sides of single scintillator elements **14** based on their location in the array **12.** The scintillator elements **14** are arranged in a MxN array without adhesives forming an air gap **16** between scintillator elements **14**.

[0037] The scintillator elements **14** are bonded to a light guide **24** using a bonding agent **18**. The light guide **24** is positioned above a plurality of photodetectors **26**. The thickness and material of the light guide **24** is selected to optimize the light guide **24** for the geometrical set up of the photodetectors **26** and the light emission properties of the scintillator elements **14**, respectively. The photodetector **26** is selected from, but not limited to, a photomultiplier tube, an avalanche photodiode, a pin diode, a CCD, or other solid state detector. In this arrangement, the scintillator elements **14** disposed within the array **12** serve to detect an incident photon and thereafter produce a light signal corresponding to the amount of energy deposited from the initial interaction between the photon and the scintillator element **14**. The structure of the array **12** serves to reflect and channel the light down the scintillator element **14**, through the light guide **24** and to the coupled photodetector **26**. The signal generated by the photodetector **26** is then post-processed and utilized in accordance with the purpose of the imaging device.

[0038] FIG. 7 illustrates the positional relationship between a detector array **12** and a 3 x 3 rectangular array of photodetectors **26** used for testing. The detector array **12** is comprised of a 13 x 13 array of scintillator elements **14**. FIG. 8 illustrates a flood source image of the detector array **12** when irradiated with a radioactive point source using the array of photodetectors **26** illustrated in FIG. 7. FIG. 10 is a graphical illustration of the cross-section of the position profiles of a single row of scintillator elements **14**. Energy resolution values for all of the scintillator elements **14** are measured to be 10-15% and peak-to-valley ratio (PVR) is estimated as 2.25.

[0039] FIG. 11 illustrates the positional relationship between a detector array **12** and a hexagonal array of photodetectors **26** used for testing. The detector array **12** is comprised of a 13 x 13 array of scintillator elements **14**. FIG. 12 is a flood source image acquired by flood irradiating the detector array **12** of FIG. 11 with a radioactive point source. FIG. 13 is a profile of a single row of scintillator elements **14** of the detector array **12** used to acquire the position profile map of FIG. 12. FIG. 14 is a graphical illustration of the energy peaks of each scintillator element **14** of the detector array **12** used to acquire the position profile map of FIG. 12. The PVR in this embodiment is estimated as 3.09.

[0040] In another embodiment of the present invention, two 13 x 13 detector arrays **12** of scintillator crystals **14** are placed on a hexagonal PMT array as illustrated in FIG 15. FIGS. 16 and 17 illustrate a flood source image for two cases using two detector arrays **12**. In the flood source image of FIG. 16, a 2 mm air gap is defined between the two detector arrays **12**. It will be understood by those skilled in the art that the detector arrays **12** may be spaced at other than a 2 mm spacing depending upon the particular application. In the flood source image of FIG. 17, a mechanism **18** defining a height of 8 mm and a thickness of 0.08 mm is disposed around each detector array **12**. Each mechanism **18** is placed flush with the top side of the detector arrays **12**. Separation between the detector arrays **12** is more distinct for the case in which a mechanism **18** (FIG. 17) is used. However, the average light output for a scintillator element **14** is 5% less in this case as compared to the embodiment producing the image of FIG. 16.

[0041] In a further embodiment, the output of FIG. 16 is accomplished by varying the finish on the outside faces of the scintillator crystals **14** comprising the outside surfaces of the detector arrays **12** as compared to the scintillator crystal **14** faces disposed on the interior of the detector arrays **12**. By creating an optical variance between these sets of scintillator crystal **14** faces, the optical transmission from one detector array **12** to another is decreased.

[0042] From the above description, it will be recognized by those skilled in the art, that a detector for use in imaging applications such as X-ray imaging, positron emission tomography (PET), computed tomography (CT), gamma camera and digital mammography systems has been disclosed. The detector utilizes individual crystals optically coupled to a continuous light guide, the light guide having no cuts. The light guide thickness is optimized based on the shape of the photomultiplier tube array, the shape of the photomultiplier tubes and the size of the photomultiplier tubes. The present invention eliminates time required to machine the light guide to create slots or grooves, filling powder or painting.

[0043] While the present invention has been illustrated by description of several embodiments and while the illustrative embodiments have been described in considerable detail, it is not the intention of the applicant to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will readily appear to those skilled in the art. The invention in its broader aspects is therefore not limited to the specific details, representative apparati and methods, and illustrative examples shown and described. Accordingly, departures may be made from such details without departing from the spirit or scope of the general inventive concept.